General Electric Advanced Technology Manual

Chapter 4.4

Pre-Conditioning Interim Operating Management Guidelines

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4.4 PRE-CONDITIONING INTERIM OPERATING MANAGEMENT RECOMMENDATION (PCIOMR)

Learning Objectives:

1. Describe pellet-clad interaction type fuel failure.

2. Explain the purpose of PCIOMR.

3. Describe the basic PCIOMR rules.

4. Define the following terms:
   - threshold
   - PC envelope
   - ramp rate

4.4.1 Introduction

During rapid power increases above previous operating levels, thermal expansion of the fuel pellets can produce Pellet Clad Interaction (PCI) that causes high localized stress in the cladding. When these stresses occur in the presence of fission products, the PCI may cause failure of the cladding. The defects generally appear as longitudinal tight cracks, and for power levels typical of 8x8 fuel designs, occur at exposures beyond 5000 MWd/t.

One of the measures taken to counteract the PCI failure in operating BWRs was a procedure for limiting the number and types of sudden power increases that produce levels above previous operating values. This procedure is called the Preconditioning Interim Operating Management Recommendation (PCIOMR).

The PCIOMR is based on results of plant surveillance, fuel inspections, and individual fuel rod testing in the General Electric Test Reactor (GETR). Tests at GETR in 1971 and 1972 confirmed the mechanism and characteristics of the PCI failures observed in operating BWRs during rapid power increases. Beginning in late 1972 and early 1973 a series of tests in GETR using early production fuel rods demonstrated that a slow ascent to power would not only prevent fuel failure, but that the slow ramp "preconditioned" the fuel to withstand subsequent rapid power changes at all levels up to that attained during the initial slow power increase (PC envelope). These tests served as the bases for the PCIOMR that was introduced in mid-1973.

Subsequent testing, and as surveillance of operating reactor experience, has allowed some modifications to the original procedures. These modifications include more flexibility at low exposures through use of a higher power level (often referred to as the threshold power) for initiation of the preconditioning ramp, by use of maintenance procedure which allows retention of preconditioning for extended exposures. In 1978 a faster preconditioning ramp rate was introduced as a result of testing and analysis of GETR and operating data.

Since its introduction, the PCIOMR has been successfully implemented in operating BWRs throughout the world. The procedure has demonstrated its effectiveness in generally reducing the incidence of PCI failures on the earlier 7x7 fuel designs. In addition, the performance of newer fuel designs has been excellent when the PCIOMR is utilized. Not only has it been proven technically effective, but modifications to the procedure, and introduction of implementation aids and guides have made the PCIOMR a viable means for mitigating the effects of pellet-clad interaction.

4.4.2 Pellet Cladding Interaction

Pellet-clad interaction (PCI) failure of zircaloy clad fuel can occur during rapid power increases in irradiated fuel. Reactor operation produces fuel cracking and radial relocation of pellet fragments and also increases concentrations of fission products such as iodine and cadmium. The differential pellet-clad thermal expansion that occurs during a power increase may then cause pellet-clad interaction with high localized stresses. In the presence of embrittling species (I and Cd), stress corrosion cracking may occur. The incidence of PCI failures depends on absolute power, rate of increase in power, duration of the power increase, previous power history and burnup. Also, there is a power threshold below which failures do not occur. This power threshold is a function of fuel burnup.

For PCI to occur, both a chemical embrittling agent (fission products I and Cd) and high cladding stresses are necessary. High cladding stresses occur at the pellet-to-pellet interfaces where PCI cracks are most commonly found. Strain concentrations occur in the cladding at radial pellet crack locations. The strain concentration is enhanced where the strain, due to pellet cracks, is also at the location of strain at pellet-to-pellet interfaces. (see Figures 4.4-1, 2, and 3.)

4.4.3 PCIOMR Rules

The General Electric operational recommendations (PCIOMR) are used to reduce PCI failures. Below the threshold power at which PCI failure occurs, there are no limitations on the magnitude, or rate, of power increase. Above the threshold, slow rates of power increases are accomplished by flow control according to PCIOMR guidelines developed from tests in experimental reactors. Following the slow increase to power levels above the threshold a "preconditioned power" level is established which may be utilized for an extended period of time. The PCIOMR rules listed in Table 4.4-3 have significantly reduced PCI fuel failures.

4.4.4 Maintenance of PC Envelope

Initial preconditioning of the fuel, at the beginning of each cycle, cannot be avoided. The preconditioning process itself, namely the slow and controlled increase in local power levels above the preconditioning threshold, must occur at the prescribed rate. At the start of each fuel cycle, the first preconditioning ramp to full power is insufficient to precondition all of the fuel. This is due to some nodes being controlled and, as such, are operating at power levels below the preconditioning threshold. During the first control rod sequence exchange, these low power nodes become uncontrolled and require preconditioning. Hence, a second preconditioning ramp will be necessary. Upon completion of this second ramp, all the fuel will have had an opportunity to be preconditioned. Throughout the remainder of the operating cycle, utilization of proper envelope maintenance and flux shaping techniques will eliminate further preconditioning ramps from low power levels (50 to 75% of rated).

For the purpose of this discussion, the fuel in the core may be regarded as either "A" fuel or "B" fuel as determined by the bundle location in-core. If the bundle is uncontrolled at 50% control rod density in A sequence, then the bundle is A fuel. Likewise, B fuel is uncontrolled at 50% control rod density in B sequence. Note again that during reactor operation in A sequence, all of the A fuel is uncontrolled. During B sequence operation, all of the B fuel is uncontrolled.

Refer to Figure 4.4-8. Assume a beginning-of-cycle startup in the A-1 sequence. At 1,000 MWd/t (core-averaged) cycle exposure, the controlling rod pattern is changed to the B1 sequence. At 2,000 MWd/t cycle exposure, the controlling rod pattern is changed to the A2 sequence and so on as shown. The actual ordering of A1/B1/A2/B2 sequence operation is not important. However, it is essential that the A and B sequences are alternately employed. The A1/B1/A2/B2 sequence that is illustrated here is just one such possibility. As explained later on, preconditioning time will be minimized if the control rod pattern in each sequence results in a bottom-peaked power distribution, preferably Haling or better, at all radial locations. During the beginning-of-cycle startup (Figure 4.4-4 and 5), all fuel will be limited to their exposure dependent preconditioning threshold values.

The exposed fuel will be most limiting due to its having the lowest threshold. There is a shortcut for the beginning-of-cycle startup. It is imperative that the power distribution in the initial sequence be properly bottom peaked. For high power density cores loaded with 7x7 fuel, attainment of a proper bottom peak at the beginning-of-cycle may require more than one preconditioning ramp. All other cores can attain the desired power distribution on the initial ramp.

Upon reaching rated power and completion of the 12-hour soak, the preconditioned envelope should be stored for all nodes. Those nodes which are controlled will not have benefitted from the preconditioning ramp just completed. Despite this envelope update, they shall remain limited in power level to their preconditioning threshold values. All of the remaining nodes are uncontrolled and if their peak pin power levels had been preconditioned above their threshold power levels, new preconditioned envelope values will be retained. All of the A fuel (assuming initial operation in A1 or A2 sequence per Figure 4.4-5) and some of the B fuel will therefore have had an opportunity to expand their preconditioned envelope. The A fuel bundles will now have a preconditioned envelope distribution similar to their axial power distribution with the exception of a few nodes near core top and core bottom for which the final power level is still below the preconditioning threshold. Figure 4.4-6 illustrates conversion of the axial power to segment preconditioned envelope values for the A fuel. As for the B fuel, some segments that are situated above the control blade tips may have their preconditioned envelope updated if their final power levels exceed the preconditioning threshold. The important aspect here is that the A fuel, which is wholly uncontrolled, has a valid bottom-peaked preconditioned envelope. Should the reactor be shut down during the first 1,000 MWd/t a rapid return to rated power with the same rod pattern will now be possible utilizing the preconditioned envelope stored at the beginning-of- cycle. If a slower return to rated power is acceptable, it would be best to start up in a new sequence (i.e., B1 or B2 if the beginning-of-cycle start up was in A1 or A2 sequence). This would postpone the sequence exchange scheduled for 1,000 MWd/t cycle exposure until 1,000 MWd/t plus the cycle exposure at the time of the reactor shutdown.

Just prior to reducing core flow and power level for a control rod sequence exchange at 1,000 MWd/t cycle exposure, the preconditioned envelope should again be updated for all nodes. The envelope stored at the beginning-of-cycle will have expired shortly after this power reduction. The preconditioned envelope update at this time constitutes envelope maintenance; the envelope validity will be extended for a second core average exposure of 1,000 MWd/t period. This step is important because it permits utilization of the bottom-peaked preconditioned envelope for the A fuel during the control rod sequence exchange and ensuing power ascension at 2,000 MWd/t cycle exposure.

Following the preconditioned envelope update at the completion of A1 sequence operation, the core thermal power is reduced and a control rod sequence exchange to the B1 sequence is performed. The power ascension in the B1 sequence rod pattern will again be a lengthy preconditioning process. This cannot be avoided because the B fuel segments which were controlled during the A1 sequence operation are now uncontrolled. This fuel will require preconditioning from their preconditioning threshold values.

As in the beginning-of-cycle A1 sequence rod pattern development, it is essential that the necessary time be scheduled to ensure a proper, bottom- peaked power distribution during rated power operation in the new B1 sequence rod pattern. If time is going to be spent on preconditioning, it will be best utilized if the bottom of the core is being preconditioned.

Following this B1 sequence preconditioning envelope update, all of the fuel bundles will have had an opportunity to have its entire axial length preconditioned. The A fuel during A sequence operation; the B fuel during B sequence operation. The preconditioned enveloped formed reflects the maximum power level for each and every fuel segment in the core from either A or B sequence. This resultant preconditioned enveloped is referred to as a composite envelope.

As was the case during the first 1,000 MWd/t period of cycle operation in the A1 sequence, should the reactor scram or be shut down during the present B1 sequence operation, a rapid return to rated power will be possible.

At the close of the 1,000 MWd/t cycle operation in the B1 sequence, it is necessary to update the preconditioned envelope for those nodes and only for those nodes that were updated earlier during the B1 sequence operation. OD-11 has the capability to distinguish these nodes from all other nodes via the nodal delta exposure histogram edit of option 1. (All of the other nodes would have to have been updated at the end of the A1 control rod sequence operation -- the option 1 edit will show the largest value of delta exposure for these nodes. Those nodes that were updated during B1 control rod sequence operation will have smaller values of delta exposure as their preconditioned envelope values were updated more recently.) By updating the B1 sequence nodes, the preconditioned envelope for these nodes will be maintained for another 1,000 MWd/t. That is, their preconditioned values will be valid until the control rod sequence exchange to the B2 sequence and the ensuing power ascension at 3000 MWd/t cycle exposure.

At 2,000 MWd/t cycle exposure, core thermal power is reduced, the control rod pattern is changed to the A2 sequence and core thermal power is increased to rated. During this maneuver, all nodal powers are limited to their preconditioned envelope values. Only those nodes which did not operate at a power level above the threshold level during the A1 and B1 sequences will be limited to the threshold values. If good bottom burns were obtained in both sequences, then all of the fuel will now have large preconditioned envelope values at the core bottom. Once the target A2 control rod pattern is set, core flow can be increased until the first nodal power reaches its preconditioned envelope value. Experience shows that between 80 to 90% of rated core thermal power will be reached before the preconditioning envelope is encountered. The power level attained increases with increased similarity among the previous A1, B1, and present A2 power distributions. The rod positions in the new A2 control rod pattern are irrelevant as long as the power distribution obtained is properly bottom-peaked at all radial locations in the core. The key to successful application of envelope maintenance is to ensure that every control rod pattern utilized results in a good power distribution. The more consistent the core power distribution from sequence to sequence, the faster and easier it will be to return to rated power following a control rod sequence exchange or plant outage.

When rated power in the A2 sequence is achieved, the preconditioned envelope values stored at the end of A1 sequence operation will no longer be valid as it has been over 1,000 MWd/t since these values were stored. These nodes can be distinguished and updated independently from the nodes whose preconditioned envelope values were updated at the end of B1 sequence operation by using the option 1 histogram edit of OD-11. At this time (in the A2 sequence) all of the A fuel bundles will again be completely uncontrolled. Just prior to the control rod sequence exchange from the B1 sequence, when the preconditioned envelope was updated, all of the B fuel bundles were completely uncontrolled. Hence, this new composition envelope is also comprised of uncontrolled nodal power levels for all of the fuel.

If the preconditioned envelope is properly updated following every ascension to rated power, and if the preconditioned envelope is properly updated prior to each power reduction and control rod sequence exchange, then the stored preconditioned envelope will always (except during the first 1,000 MWd/t cycle exposure) be a composite envelope and each node's preconditioned power level will be determined from its maximum uncontrolled power level. If the plant has the new GE computer code, the plant can go to 2000MWD/t on a nodle bases.

Table 4.4-1 PCI Program

1971	Initiate extensive test and development program.
1972	Initiate design change (7x7R, 8x8)
1973	Implement PCIOMR (7x7R in operation)
1974	Convert to 8x8
1977	8x8R production begins
1979	Pre-pressurized production starts (P8x8R) Test and Development continues Control Cell Core testing
1981	Barrier Fuel commercial testing

Table 4.4-2 PCI Related Design Changes

Design Change	Benefits
Pellet Geometry eliminate pellet dishing • shorten pellet • chamfer pellet edges	Reduce local clad strain
Cladding Heat Treatment • increase annealing temperature	Reduce variability in clad ductility
8 x 8 Lattice Change	Lower fuel duty • 18.5 kW/ft vs 13.4 kW/ft
Pressurization	Improves pellet-to-cladding gap conductance Lower fuel temperatures Reduced UO_2 thermal expansion reduced fission gas release
Control Cell Core	Simplified operation
Barrier Commercial test	PCI Resistant

Table 4.4-3 PCIOMR Rules

1	No constraints below preconditioning threshold.
2	Preconditioning threshold is exposure dependent.
3	Limit control rod movement above threshold.
4	Rod withdrawal over threshold permitted one notch every two minutes.
5	For xenon or burnup, one notch every 12 hours.
6	Rate of power increase with flow at .11 kW/ft/hr above threshold.
7	Ramp rate permitted at .12 kW/ft/hr if over four hours.
8	Maximum ramp increase at .2 kW/ft (one step).
9	.3 kW/ft over envelope permitted during xenon transient (no control rod movement or flow increase).
10	Power increases at 15 % power/minute with flow permitted if below preconditioned level.
11	Soak 12 hours to establish preconditioning envelope when desired power level is obtained.
12	Envelope is good for 1,000 MWD/T after leaving the envelope. Establish new envelope after 1,000 MWD/T.
13	Can preserve the envelope for 1,000 MWD/T if you soak at the envelope in 72 out-of 96 hours.

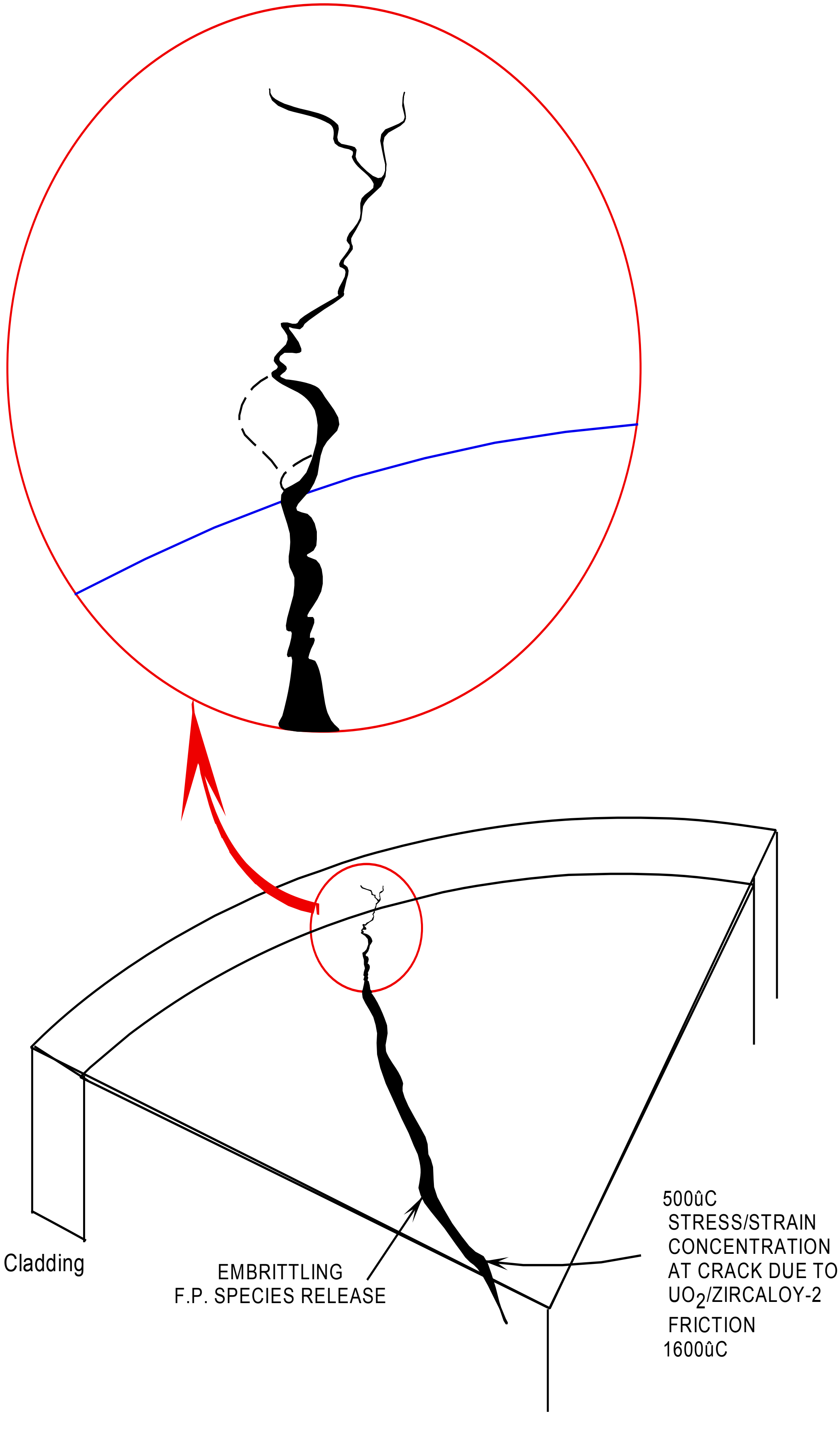


Figure 4.4-1 PCI Failure Mechanism

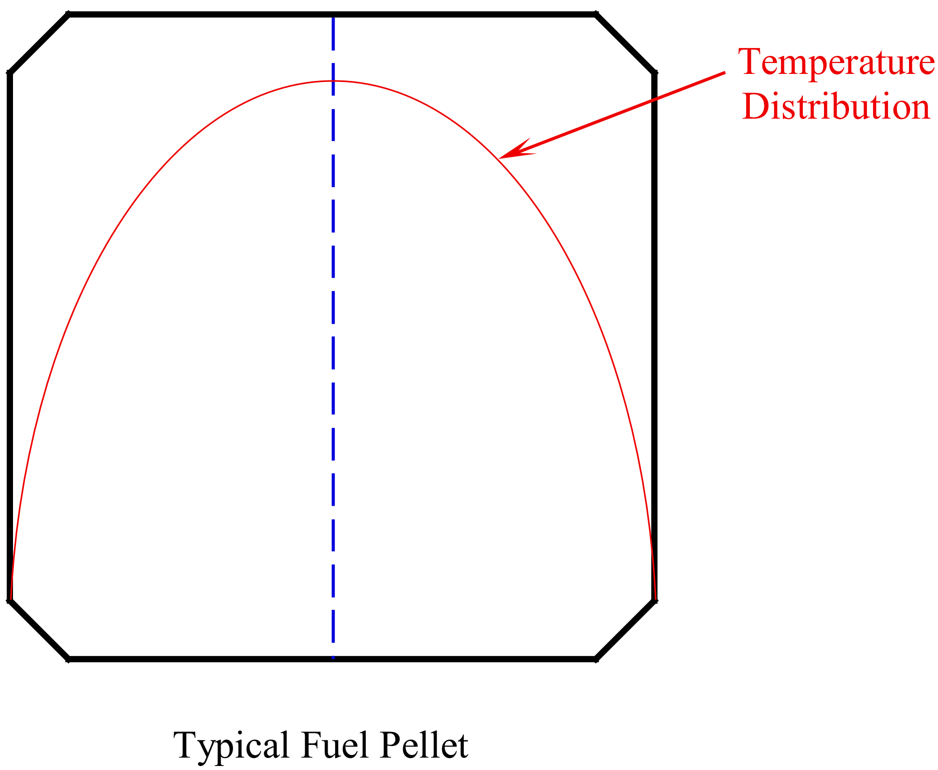


Figure 4.4-2 Typical Temperature Distribution

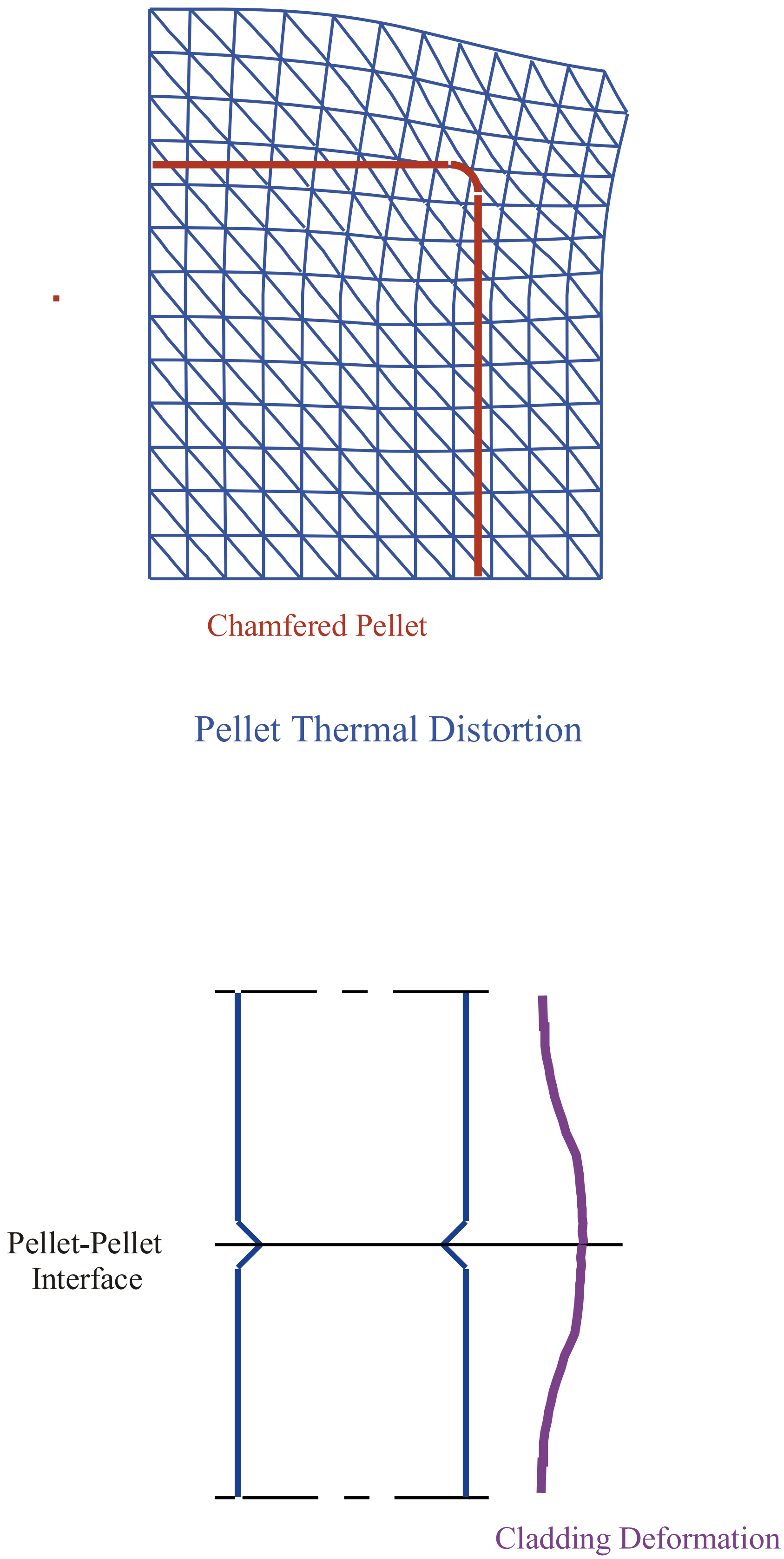


Figure 4.4-3 Pellet-Clad Interaction

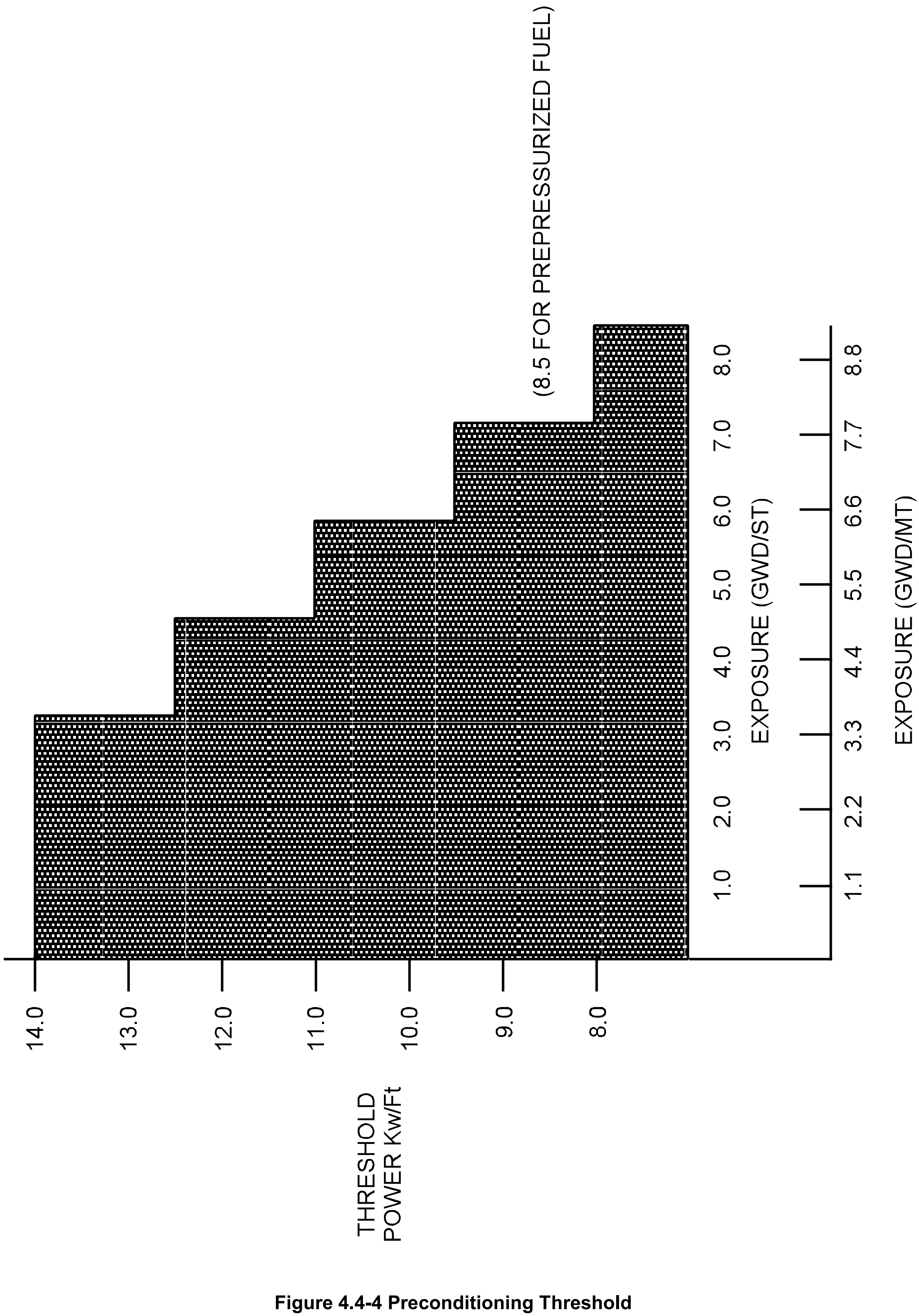
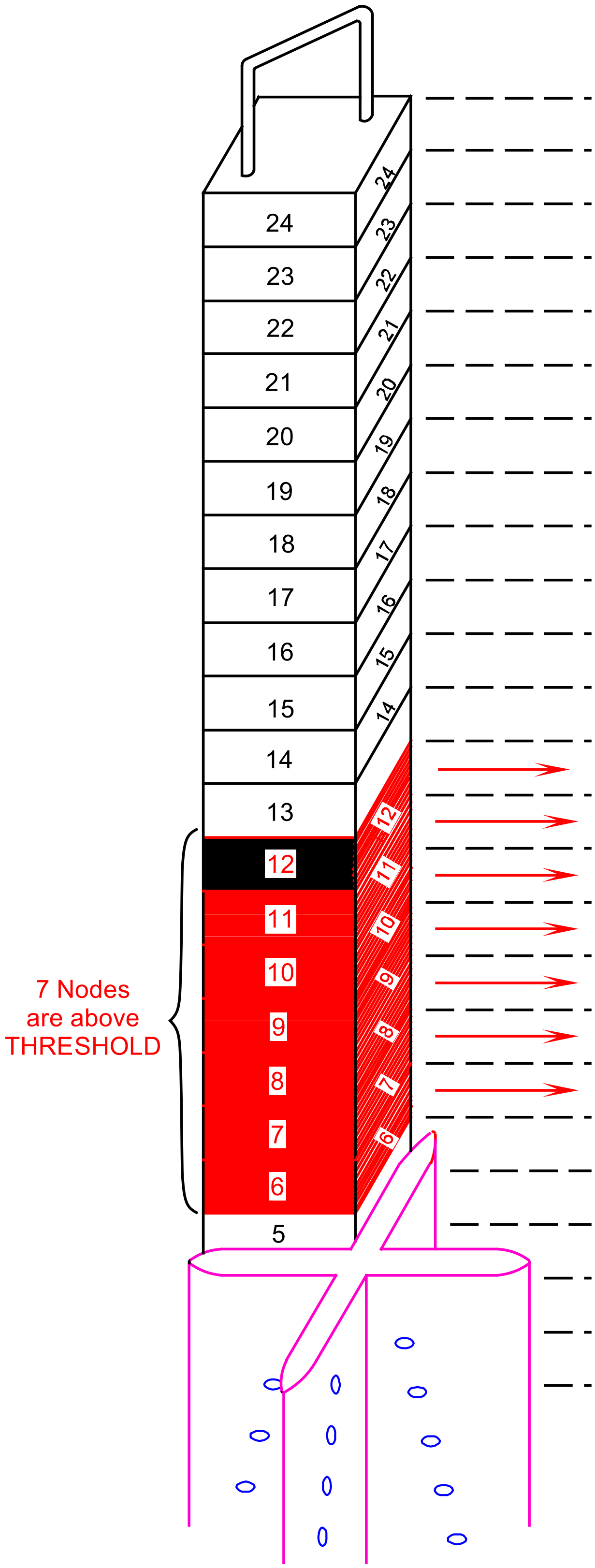


Figure 4.4-4 Preconditioning Threshold



NODAL POWER kw/ft	THRESHOLD kw/ft	ENVELOPE
3.2	8.0	8.0
3.3	8.0	8.0
3.4	8.0	8.0
3.5	8.0	8.0
3.7	8.0	8.0
3.9	8.0	8.0
4.0	8.0	8.0
4.2	8.0	8.0
5.0	8.0	8.0
6.1	8.0	8.0
6.9	8.0	8.0
7.5	8.0	8.0
8.1	8.0	8.1
8.4	8.0	8.4
8.8	8.0	8.8
9.0	8.0	9.0
9.3	8.0	9.3
8.9	8.0	8.9
8.4	8.0	8.4
7.8	8.0	8.0
2.8	8.0	8.0
2.7	8.0	8.0
2.4	8.0	8.0
2.3	8.0	8.0

Figure 4.4-5 Fuel Assembly Nodal Power/Threshold/Envelop

Lattice	6x6	7x7	7x7R	8x8	8x8R	P8x8R				
Clad	SS	Zr-2				Zr-21 Barrier				
Designation		GE-2	GE-3	GE-4	GE-5	GE-6	GE-7	GE-8	GE-9	GE-10
Introduced		68	73	74	77	79	83	86	88	89
Active Fuel Level		144	146	148	150					
GWs/Mt Peak Pin Exp.	—	—	—	—	—	—	~45	65		
$\#Gd_2O_3$ Rods, Max	—	—	—	—	—	—	8	12	13	
Axial Gd-Reloads	—	—	—	—	—	—	—	Ã	Ã	Ã
Axial Enrichment	—	—	—	—	—	—	—	—	Ã	Ã
Max. Pellet Enr.	—	—	—	—	—	3.95				4.95?

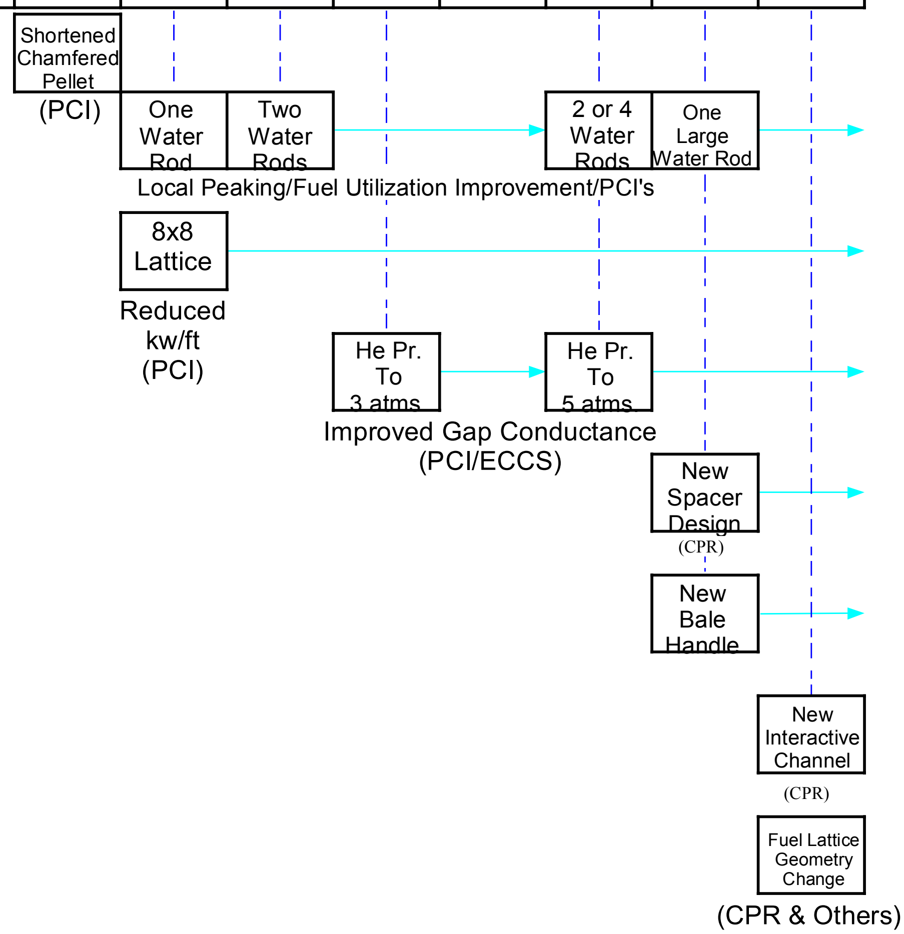


Figure 4.4-6 Fuel Design Evolution

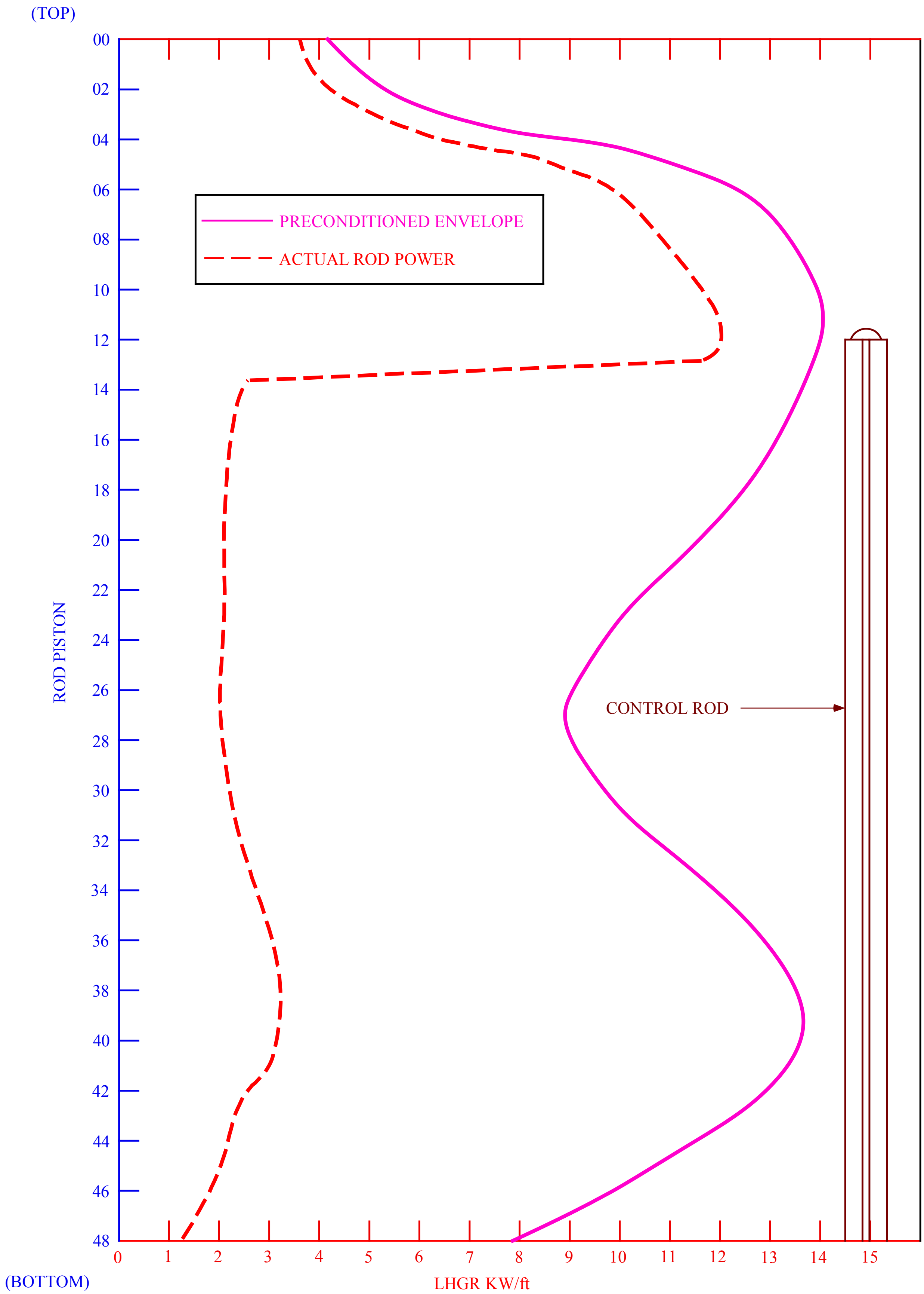


Figure 4.4-7 Preconditioned Envelope and Actual Rod Power

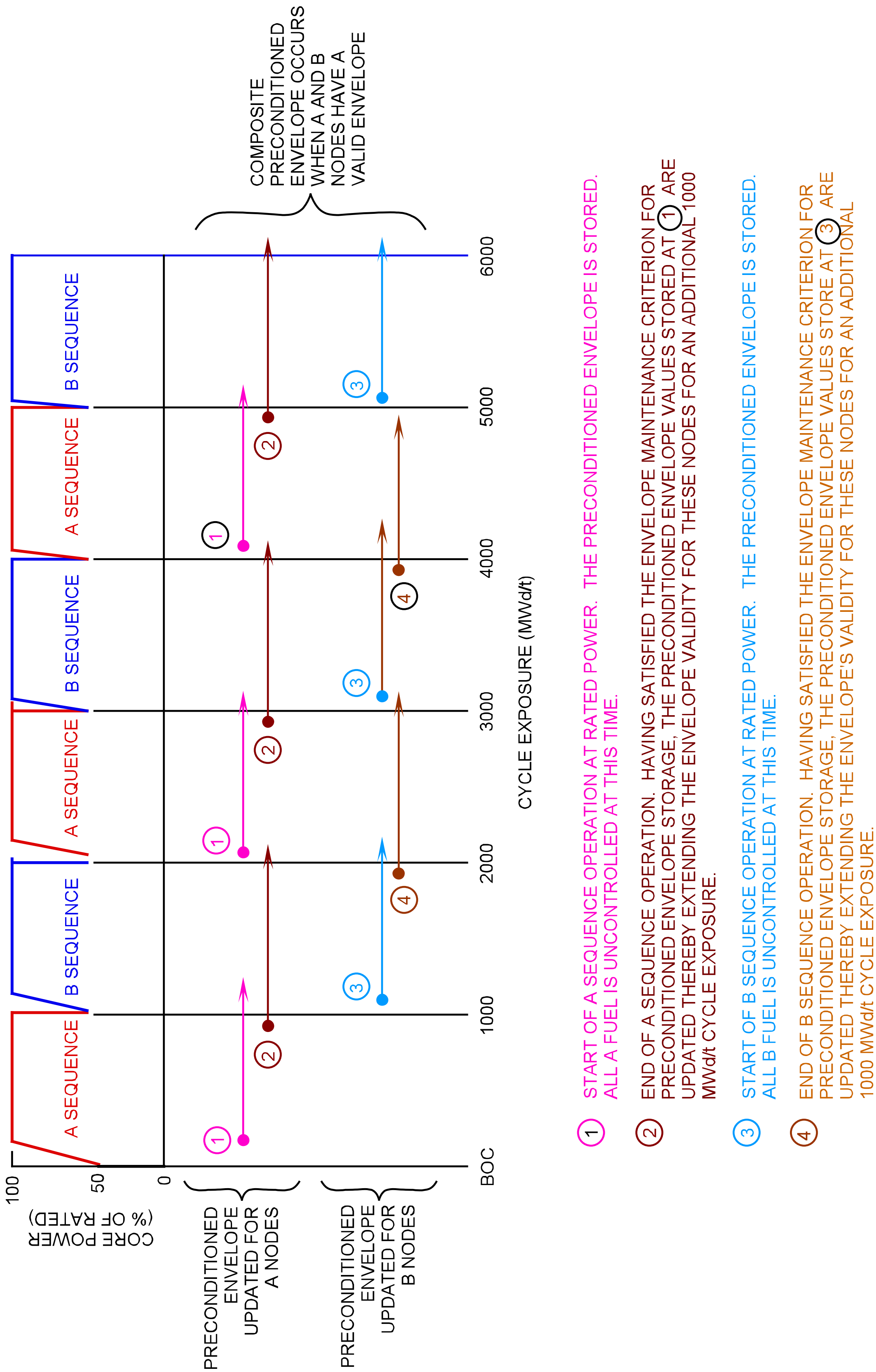


Figure 4.4-8 Strategy for Maintaining a Composite Envelope